

Nanometrology

The burgeoning field of nanomaterials extends across the full range of traditional material classes, including all forms of metals, polymers, and ceramics. No previous materials technology has shown so prodigiously a potential for concurrent advances in research and industry as does the field of nanomaterials in mechanical devices, electronic, magnetic, and optical components, quantum computing, tissue engineering and other biotechnologies, and as-yet unanticipated exploitations of as-yet undiscovered novel properties of nanoscale assemblies of particles. Already, there is growing excitement surrounding the ability of some molecules or particles to self-assemble at the nanoscale to form new materials with unusual properties. Nanometrology, *i.e.*, the ability to conduct measurements at these dimensions, to characterize the materials, and to elucidate the structure and nature of these new and novel assemblies, is a requisite and fundamental cornerstone that must be established securely if this technology is to flourish.

NIST is uniquely positioned to lead the development of the measurement methods, instrumentation, standards, and reference materials that, together, will form the metrological infrastructure essential to the success of nanotechnology.

The MSEL Nanometrology Program incorporates basic measurement metrologies to determine material properties, process monitoring at the nanoscale, nanomanufacturing and fabrication techniques, and structural characterization and analysis techniques such as advanced imaging and multiscale modeling. The Program comprises 22 projects in the Ceramics, Materials Reliability, Metallurgy, and Polymers Divisions, and includes structural characterization using neutron scattering at the NIST Center for Neutron Research (NCNR). The projects cover a wide range of measurement and characterization methods grouped into the areas of mechanical property measurement, chemical and structural characterization and imaging, fabrication and monitoring of nanoprocesses and events, and modeling of nanoscale properties. In each area, we work to advance basic measurement capabilities and lead the intercomparison, standardization, and calibration of test methods. The newly completed Advanced Measurement Laboratory at the NIST Gaithersburg site provides an incomparable environment for accurate nanoscale metrology.

In the area of mechanical property measurement, we are developing and standardizing techniques for determining nanoscale elastic properties (elastic moduli, Poisson's ratio, and internal stress), plastic deformation, density, adhesion, friction, stiction, and tribological behavior. Work in nanoindentation, used extensively

in determining mechanical properties of thin films and nanostructures, focuses on developing traceable calibration methodologies and standard test methods. We also use atomic force acoustic microscopy, surface acoustic wave spectroscopy, and Brillouin light scattering to measure the mechanical properties of thin films. In addition, we are developing micro- and nano-scale structures and test methods to measure strength and fracture behavior of interfaces and materials having very small volumes.

The chemical and structural characterization and imaging utilize neutron and x-ray beam lines at three facilities: the NCNR; the National Synchrotron Light Source at Brookhaven National Laboratory; and the Advanced Photon Source at Argonne National Laboratory. Innovative scattering and spectroscopy methods are advancing our ability to obtain a wide range of chemical and structural information at the nanoscale, including chemical bond identification and orientation, polyelectrolyte dynamics, and equilibrium structures. In collaboration with three other NIST laboratories, we are developing electron microscopy and spectroscopy instrumentation for quantitative, 3D chemical imaging at the nanoscale. Other characterization projects include work on gradient reference specimens for the calibration of advanced scanning probe microscopy, and the application of carbon nanotubes as physical probes of cell membranes.

Efforts in the fabrication and monitoring of nanoscale processes and events include the study of electrochemical and microfluidic methods for fabricating nanostructures, novel approaches to nanocalorimetry for the study of interfacial reactions, *in situ* observations of nanoparticle and nanotube dispersion and alignment, and advanced instrumentation for nanotribology experiments.

Finally, we have extensive efforts in the theory, modeling, and prediction of material properties and behavior extending from nanoscale to macroscale dimensions. Modeling efforts include large-scale finite element methods, multiscale Green's function methods, classical atomistic simulations, first principles, and quantum mechanical calculations using density functional theory. Often, several modeling methods must be combined into one study to accurately describe the material behavior; thus, we pay great attention to the correct interfacing between models operating at different length scales, to ensure that our models properly capture the physics of both components and total systems.